arXiv:astro-ph/0403554v1 23 Mar 2004

Extreme Physics via X-rays from Black Holes and 'Neutron' Stars

Martin Elvis[a] *

[a]Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge MA 02138 USA

A combination of microchannel plate optics and a 32×32 pixel microcalorimeter would allow the successor to the *Rossi XTE* to explore new domains of spectroscopic timing in a MIDEX class mission. With ~10 times the area and ~100 times the spectral resolution of the PCA (and 10 times that of silicon detectors) such a mission would be able to explore redshifts and plasma conditions in weak line features over a wide range of celestial sources. This would allow several tests of basic physics, both QED/QCD and GR.

1. AN EXTREME PHYSICS MISSION

Question 6 in the Turner report[1] *Connecting Quarks to the Cosmos* asks **"What are the limits of physical law?"**. The report goes on to point to black holes and neutron stars as the places that could best test these limits. Both types of compact object are seen primarily through X-ray radiation emitted close to their surface or event horizon, derived from gas accreted onto them from a closely orbiting companion star. In principle these X-rays could probe the physics near these exotic objects. Here we show how to tackle Question 6 head on, using a novel combination of technologies to build an X-ray detection system for the signals from these cosmic laboratories.

By combining high spectral resolution with high time resolution this mission allows the study of weak emission and absorption lines, and potentially polarization, in celestial X-ray sources. In this way we can probe matter under conditions more extreme than could be produced in any terrestrial laboratory for strong gravitational or magnetic field. Spectral lines are especially good "clocks" for GR, and are sensitively affected by the ultra-strong ($\sim 10^{15}$g) magnetic fields in magnetars (Table 1). For example in QED compression of the wavefunction perpendicular to the B-field in magnetars will move the Lyman series up to X-ray wavelengths.

Space missions that address fundamental physics tend to be single experiments. This mission would, in contrast, operate as a fundamental physics facility with multiple experiments, like Fermilab or CERN, but with X-ray sources, such as the black hole Cygnus X-1 or the magnetar SGR 1806-20, taking the place of the accelerator. As **a physics mission** this satellite would only produce X-ray binary astrophysics incidentally, although we expect that a great deal of X-ray binary astro-physics will be a by-product of the primary mission. Physics topics that could be addressed span both pillars of 20^{th} century physics, Quantum Electrodynamics and General Relativity. In Table 1 we begin an enumeration of the extreme physics that could be addressed.

Table 1
Extreme Physics with Black Holes, Neutron Stars and Magentars

Physics	Sample Method
QED in Strong magnetic fields	Magnetars[2][3]
QCD Strange (Quark?) Matter	Equation of State of Neutron Stars[4]
GR frame dragging	black hole QPOs, lines [5]
GR metric in strong gravity	Fe-K lines, and low energy 'satellite' lines, in X-ray binaries, AGNs[6]

The *Rossi X-ray Timing Explorer, RXTE* has had a tremendous impact on our knowledge of the properties of these objects which have the most extreme physics in the Universe. The asrophysics of these objects - their gas flows and radiation

*elvis@cfa.harvard.edu

emission mechanisms - are now understood at a level of detail unimagined 10 years ago. Instead of being mysterious objects of investigation, X-ray binaries are becoming tools for the investigation of fundamental physics near neutron stars and black holes. To realize this potential requires a qualitative leap beyond *RXTE*. Precise spectral measurements beyond the ~10% resolution of RXTE above 2 keV, or XMM-Newton at ~1 keV are essential, yet with many times the collecting area of *Chandra*, to collect sufficient photons.

The value of spectral resolution is shown by the goal of measuring the radius of a neutron star and so determining its equation of state. This will tell us if these are truly 'neutron' stars or something more exotic: strange stars. The gravitational redshift of an atomic line feature from a neutron star surface measures the radius of the star, and hence the constrains the equation of state. Such a line has been seen, but to limited accuracy. A factor 10 or more improvement in spectral resolution would let us test models. The need for collecting area is illustrated, for example, by Quasi-Periodic Oscillations (QPOs). Since QPOs in X-ray binaries could be the key to exploring General Relativity (GR) in the strong gravity limit, this matters. The shape of QPOs is ambiguous, since we know them only through their power spectra, and co-adding is not possible because they are only *quasi*-periodic oscillations. Some 5 m^2-10 m^2 is needed to see individual QPOs.

2. THE MISSION CONCEPT

We propose a MIDEX class mission concept to achieve these goals. Microchannel plate (MCP) optics have a factor 100 lower weight to effective area ratio compared with ASCA-like foil optics, allowing the needed 5-10sq.meter mirror. At the single focus of the MCP optics would sit a microcalorimeter detector with 10-50 times the spectral resolution of the RXTE or of silicon detectors. Microcalorimeter are infeasible for non-imaging or multi-focus configurations. The mission will spend long intervals pointed at a single target. High orbits are desirable for uninterrupted viewing of sources for Fourier analysis. Table 2 shows how the mission fits within the weight envelope for a Delta 2 launcher. [The Con-X XMS calorimeter has a mass budget of 123 kg, including 90 kg for the cryo system [7].] Compared with Constellation-X, this mission has major weaknesses: poorer angular resolution is *a requirement* (for the calorimeter readout, see §2.2), no diffraction gratings, no high energy telescope. The power of the mission comes from concentrating on a niche application from an astronomy point of view, but a major field, when considered as a physics experiment.

Table 2
Strawman Mission Mass Budget

Science Payload	*Mass*
10 m^2 Microchannel Plate Optics	37 kg
Mirror support structure	37 kg
30 m Optical Bench	20 kg
Calorimeter + cryo system	123 kg
Spacecraft	200 kg
20% Reserve	83 kg
TOTAL	500 kg

The low background that comes from arcminute imaging would allow the mission to explore a wide range of celestial sources including some of the bright "Ultra-Luminous X-ray Sources" (ULXs) in external galaxies, which may be intermediate mass ($\sim10^3 M_\odot$) black holes, and bright AGN hosting $\sim10^6$-$10^9 M_\odot$ black holes.

2.1. Microchannel Plate Optics

The key technology is MCP optics. With their area:mass advantage a 10 m^2[8] the MCP mirror would weigh only 37 kg (plus an equal mass support structure). MCP optics have high aperture utilization (>75%), and the dense packing of MCP optics close to the optical axis gives significant response above 10keV, which could be increased by using a longer optical bench. Arcminute resolution has been demonstrated at 8 keV in a radially packed geometry with a circular PSF[9]. A 25 meter focal length with the same focal ratio as *Chandra* would have a 3 m dia mirror and so a geometrical area of 7.1 m^2, or an open area of 5.65 m^2 for a plausible 80% aperture utilization. Reflection efficiency would reduce this

to ~3.75 m^2 up to 2 keV. Increasing the focal length to 40 m and mirror diameter to 5 m would give 8 m^2 *effective* area in the few keV range. The plate-like geometry of microchannel plate optics allows them to be folded for launch in a compact configuration, and then deployed with simple mechanisms [9]. The ~30 meter focal length is readily achieved arcminute imaging level with flight tested extendable structures. The Able Engineering Company (AEC[10]) has supplied lightweight (Table 2) continuous-longeron coilable booms of similar lengths to several missions (UARS, GGC WIND, GGS POLAR, Cassini, Lunar Prospector, IMAGE).

2.2. Rapid Readout Microcalorimeter

A 10 m^2 mirror looking at the brightest X-ray sources needs a rapid readout detector. Typical neutron star and black hole X-ray binaries yield 10^4ct s^{-1}. Microcalorimeters have a reasonable maximum readout rate *per pixel* [11][12] of 1000 Hz. To avoid pile-up and the resultant dead time and spectroscopic/timing degradation effects, the detectors need to have a readout rate about 10 times the count rate. This is achieved by spreading the signal over >100 pixels. Such arrays are now achievable. The XRS on ASTRO-E2 (launch February 2005) has a 6×6 array. Con-X is aiming for a 32×32 array[13]. The plate scale for a 30 meter focal length optic is 150μm/arcsecond, so a 1 arcminute PSF would spread over 9 mm. An 18 mm dia. 32×32 array would have a pixel size of ~600 micron. The XRS is ~4 mm dia and so only modest changes in size and heat capacity are required.

2.3. Polarimeter

X-ray polarimetry can provide a whole new diagnostic for the physics in high magnetic and gravitational fields [14], [15]. But polarization measurements are photon hungry. To measure a typical polarization of 1% to ±10% needs 10^6 photons (while a 10% total flux measurement needs only 100 photons) and so has never been achieved. A 10 m^2 mirror is just what is needed. The large field of view of MCP optics, compact dewar designs and closed cycle refrigerators may allow an X-ray polarimeter [16] to be included.

3. EXTREME PHYSICS EXPLORER: A FITTING SUCCESSOR TO *Rossi XTE*

This concept is of an **extreme physics mission**, achieved through opening up orders-of-magnitude of new timing/spectroscopy/polarimetry territory. Yet the mission fits within the MIDEX envelope, and so can plausibly be brought to fruition on a modest timescale. The next step is to have community meetings focussed on the physics to be done, and on the mission technologies that can make it happen. Such meetings needs to involve the high energy physics community and the high energy astrophysics community working together.

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